

SPECIFICATION

TITLE: A SYSTEM AND METHOD FOR INCREASING CHANNEL

CAPACITY OF FIBER-OPTIC COMMUNICATION NETWORKS

Priority of PCT/US01/21062 filed June 29, 2001 and United States Provisional Application Serial No. 60/217,136 filed July 10, 2000 are hereby claimed.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to optical communication networks and more particularly relates to a system and method for increasing the channel capacity and total system throughput of a fiber-optic communication network utilizing three-dimensional spatial field.

2. Background Information

As data communication systems and networks consume more and more bandwidth, fiber-optics has emerged as a leading technology for metropolitan and long-haul data transmissions. Access techniques, adapted from electronics communication, such as Code Division Multiplexing (CDM), Frequency Division Multiplexing (FDM), and Time Division Multiplexing (TDM) have been used in fiber-optic systems and networks. For example, Wavelength Division Multiplexing (WDM) is essentially FDM in the optical domain. To further conserve the bandwidth of an optical

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1 network, a so-called Dense WDM (DWDM) standard has been proposed  
2 with the channel separation set at 0.8 nm in wavelength, or 100  
3 GHz in frequency.

4 One area unique to optical communications has provided  
5 another dimension for capacity enhancement. This is the  
6 polarization of an optical signal. Lithium Niobate (LiNbO)  
7 phase modulators and polarization controllers, and Pockels cells  
8 have been used to implement polarization shift keying (POLSK).

9 Other investigations have considered polarization of signals in  
10 different wavelength channels. One example is in U.S. Patent  
11 No. 6,038,357 of Pan issued March 14, 2000 that discloses a  
12 fiber-optic PDM/WDM system comprising a plurality of sets of  
13 laser sources maintained at fixed polarization states. Each  
14 state represents a different channel. The design disclosed in  
15 that patent accomplishes an increase in the number of channels  
16 at the expense of using multiple sets of laser sources. Another  
17 U.S. Patent No. 6,025,944 of Mendez et al issued February 15,  
18 2000 discloses a clever but complex coding scheme to perform  
19 hybrid mixing of Wave Division Multiplexing (WDM) and Code  
20 Division Multiple Access (CDMA). The tradeoff in using a  
21 complex switching and coding method to improve channel capacity  
22 is unclear.

23 It is one object of the present invention to provide a

1 system and method for increasing channel capacity and throughput  
2 of an optical communications network by a combination of  
3 Polarization Modulation (PM), Wavelength Division Multiplexing  
4 (WDM), and Time Division Multiplexing (TDM). Time division  
5 multiplexing increases the number of available channels while  
6 polarization modulation increases the throughput.

7 It is another object of the present invention to provide a  
8 system and method for increasing channel capacity and throughput  
9 by applying space-time modulation to guided optical  
10 communications.

11 Yet another object of the present invention is to provide a  
12 system and method of increasing channel capacity and throughput  
13 by direct modulation of optical sources.

14 Still another object of the present invention is to provide  
15 a system and method for increasing transmission distance by  
16 including signal amplification with optical amplifiers inserted  
17 in the optical transmission fiber.

18 Yet another object of the present invention is to provide a  
19 system and method for increasing channel capacity and throughput  
20 in which an optical wavelength cross-connect is inserted in an  
21 optical fiber transmission line to reuse wavelengths.

22 Still another object of the present invention for  
23 increasing channel capacity of an optical network in which

1 temporal data streams from time division multiplexers are  
2 modulated on optical sources.

3 Still another object of the present invention is for  
4 increasing throughput of an optical network in which spatial  
5 data streams from time division multiplexers are modulated on  
6 outputs of optical sources by varying the polarization states of  
7 the optical field.

8 Yet another object of the present invention is to provide a  
9 system and method for increasing channel capacity and throughput  
10 which can be applied to conventional wavelength division  
11 multiplexing ring network.

12 Yet another object of the present invention is to provide a  
13 system and method for increasing channel capacity and throughput  
14 which can be applied to a conventional wavelength division  
15 multiplexing fiber-optic star coupled network of a plurality of  
16 wavelengths.

17 Still another object of the present invention is to provide  
18 a system and method for increasing channel capacity and  
19 throughput by application to a conventional wavelength division  
20 multiplexing fiber-optic data bus network operating with  
21 multiple wavelengths comprised of multiple Network Interface  
22 Units (NUI) communicating over an optical fiber network.

23 BRIEF DESCRIPTION OF THE INVENTION

1       The purpose of the present invention is to apply space-time  
2 modulation to increase channel capacity of optical communication  
3 networks by utilizing a three-dimensional spatial field.

4       The basis of the present invention disclosed herein is a  
5 direct application of the space-time modulation to guided  
6 optical communications, where a single mode fiber can be used  
7 for long-haul data transmission. The space-time modulation  
8 provides capacity expansion by utilizing the three-dimensional  
9 spatial field. The spatial modulation can be compressed in the  
10 form of spatial carriers,  $E_x$ ,  $E_y$ . The relationship of the  $x$   $y$   
11 components and its propagation direction  $z$  forms the basis  
12 functions for data transmission.

13       When the spatial dimension is not being used as in the case  
14 of a linearly polarized signal, all data loading is limited in  
15 time along the propagation axis. Assuming a space-time  
16 separable channel, the temporal information carrier on the  
17 propagation axis becomes independent of the transverse plane  
18 where the relative phase position (state of polarization) can be  
19 modulated. By utilizing both spatial and temporal modulation,  
20 total system throughput can be substantially increased.

21       In the present invention, a combination of Polarization  
22 Modulation (PM), Wavelength Division Multiplexing (WDM), and  
23 Time Division Multiplexing (TDM) technology is utilized. The

1 hardware implementation of the three-dimensional spatial field  
2 processing is simple and straight forward. Due to the special  
3 design disclosed herein, the polarization, wavelength, and time  
4 channels enjoy total independent operation from each other. The  
5 resulting degrees of freedom add flexibility in supporting  
6 multiple users in a large variety of optical network  
7 configurations and services. Furthermore, the independent  
8 operations imply more data channels can be added as the  
9 fiber-optic network grows under market demand. Thus, once the  
10 optical fibers are laid; only incremental cost is required to  
11 cover a fixed size network. The overall channel capacity in  
12 terms of number of channels as well as data rate throughput is  
13 simply the product of the contribution from individual  
14 modulation and multiplex technology. This aggregate throughput  
15 can be orders of magnitude higher than each multiplex technology  
16 itself.

17 In the system and method of the present invention using the  
18 combination of PM, WDM, and TDM technology, the TDM increases  
19 the number of available channels while the PM increases the  
20 throughput. In accordance with the present invention, the  
21 channel capacity of conventional wavelength division  
22 multiplexing network system can be significantly increased  
23 depending on the levels of polarization modulation. For a

1 typical WDM system using N signal sources transmitting to N  
2 receivers at N different wavelengths, only N communication  
3 channels are available for data transmission. The present  
4 invention effectively increases N by a factor equal to the time  
5 division multiplexing channels. This is achieved without  
6 requiring additional sets of optical or laser sources.

7 In one embodiment of the present invention, the system has  
8 direct modulation of optical sources. The system has a  
9 plurality of optical network sources each driven by a temporal  
10 path consisting of time division data from a transmitter data  
11 processor. The transmitter data processor multiplexes a  
12 plurality of input channels of data into a time division  
13 multiplex data stream of temporal and spatial data. Spatial  
14 data output of the transmitter data processor is directed to a  
15 polarization modulator while temporal data is sent to the  
16 optical source for direct modulation. Each optical source input  
17 is connected to a transmitter data processor and its output to a  
18 polarization modulator. The polarization modulator produces  
19 optical symbols corresponding to various polarization states.

20 Each polarization modulator output is sent to a Wavelength  
21 Division Multiplexer (WDM) before being transmitted through an  
22 optical fiber. The optical fiber is connected to a wavelength  
23 division demultiplexer. Each wavelength output of the

1 demultiplexer is connected to a polarization demodulator  
2 followed by direct photo-detection and then a receiver data  
3 processing circuit. The receiver data processor demultiplexes  
4 the received time division multiplex data from the received  
5 spatial and temporal data channels into a plurality of output  
6 data channels.

7 A variation of the invention includes signal amplification  
8 with optical amplifiers inserted in the single optical  
9 transmission fiber. The use of signal amplification in the  
10 optical fiber extend the transmission distance of the optical  
11 fiber for long haul applications.

12 Another optional but preferred feature of the invention is  
13 the use of an optical wavelength cross-connect inserted in the  
14 optical fiber transmission line to reuse these wavelengths a  
15 plurality of times for connecting various transmitters and  
16 receivers rather than having wavelength routing without reuse.  
17 In this embodiment, a first user can use a particular wavelength  
18 to establish a link with a second user while simultaneously a  
19 subsequent user can reuse the same wavelength and channel to  
20 communicate with yet another user. Compared to a typical  
21 wavelength division multiplexed fiber-optic network system  
22 operated with a pre-determined number of wavelengths without  
23 reuse, the total number of channels with this new design is



1 substantially increased.

2 Another object of the present invention is a system in  
3 which the optical source or sources are not directly modulated.  
4 Rather, the optical output signal from the source or sources is  
5 spatially modulated in polarization and temporally modulated in  
6 amplitude, phase, and/or frequency by a polarization modulator  
7 performing the function of space-time modulation. The  
8 polarization modulator is driven by a transmitter data  
9 processor. In most applications, indirect amplitude or indirect  
10 phase modulation is desirable to preserve the stability of the  
11 optical source. The output of each polarization modulator is  
12 sent to a wavelength division multiplexer before being  
13 transmitted over an optical fiber. The optical fiber terminates  
14 at a WDM demultiplexer. Each wavelength is then demodulated by  
15 a polarization demodulator followed by coherent detection and  
16 finally processed in a received data processor. The coherent  
17 optical detection can be implemented with a local optical source  
18 using homodyne or heterodyne demodulation techniques.

19 The method and system of the present invention can also be  
20 applied to a conventional wavelength division multiplexing ring  
21 network. In this embodiment each source is directly modulated  
22 by a transmitter data processor. The output temporal path of  
23 each transmitter data processor is directed to an optical source

1 while spatial data is sent to a polarization modulator that  
2 produces optical symbols corresponding to various polarization  
3 states as before.

4 The output of each polarization modulator is then  
5 multiplexed by a wavelength division multiplexer before  
6 transmission over an optical fiber to add/drop nodes in the ring  
7 network. Each add/drop node of multiple add/drop nodes around  
8 the ring operates at a specific wavelength providing multiple  
9 time division multiplexing channels. The specific wavelength  
10 output of the add/drop node of the ring network is then  
11 connected to a polarization demodulator. This demodulation  
12 process is followed by feeding the signals to direct  
13 photo-detection and receiver data processing. The receiver data  
14 processor demultiplexes the received TDM data from the received  
15 spatial and temporal data channels into a plurality of output  
16 data channels.

17 Each add/drop node of the multiple nodes in the ring  
18 network includes a receiver/transmitter pair. The receiver is  
19 capable of polarization demodulation, direct photo-detection and  
20 received data processing of multiple time multiplexed output  
21 channels. Transmitter reverses the operation by time  
22 multiplexing of data channels, direct modulation onto the  
23 optical source followed by polarization modulation.

1           A wavelength division demultiplexer extracts a signal at  
2   one wavelength and transmits the signal back at the same  
3   wavelength. The same operation is repeated in the next or  
4   sequential add/drop nodes of the optical fiber until it reaches  
5   the end of the ring. Access into and egress out of the ring  
6   network is under computer control. If any receiver/transmitter  
7   processor wishes to transmit signals, its transmitter sends data  
8   through the time division multiplexed channel. These optical  
9   signals pass through the WDM multiplexers and circulate around  
10   the ring. Hence, in this embodiment, the number of network  
11   users at each add/drop nodes increases by a substantial factor.

12           Another application of the system is in a conventional WDM  
13   fiber-optic star network of a plurality of wavelengths that  
14   consist of a star coupler connected to a plurality of nodes.  
15   Each node transmits at one of the optical wavelengths equal to  
16   the number of nodes to the star coupler which distributes the  
17   optical signals. One of the plurality of nodes is used as a  
18   central office for access and egress control of the network.  
19   The star coupler broadcasts any optical signals from one node to  
20   all the other nodes in the network. Each node also each  
21   receives and demultiplexes broadcasts signals from star coupler  
22   to determine whether it has messages sent from other nodes.

23           Another embodiment of the present invention is adapted to a

1 star network. Each star network has now increased its  
2 throughput by M times, while the total number of channels has  
3 gone up to  $N \times L$  times. Nodes are connected by a star coupler.  
4 Network users in the present invention at each node are  
5 allocated specific TDM channels in the transmitter/receiver data  
6 processor. The temporal data path is directed to the optical  
7 source while the spatial data is sent to the polarization  
8 modulator. The modulator produces symbols corresponding to  
9 various polarization states. The output of each polarization  
10 modulator at the particular wavelength is sent to the star  
11 coupler for distribution of the wavelength multiplexed signal to  
12 all other nodes. On the return path, the WDM signal is  
13 extracted from a WDM demultiplexer and polarization demodulated.  
14 This is followed by a photo-detector and transmitter/receiver  
15 data processor. The processor demultiplexes the received TDM  
16 data and the received spatial data.

17 The system disclosed herein can also be applied to  
18 conventional WDM fiber-optical data bus network operating with  
19 multiple wavelengths comprised of multiple Network Interface  
20 Units (NIU) communicating over an optical fiber. In the  
21 conventional WDM fiber-optic data bus network, each network  
22 interface unit, by which a user communicates over the network,  
23 has multiple fixed wavelength optical transmitters and multiple

1 receivers. Due to hardware cost of installing multiple pairs of  
2 transmitter/receivers for network interface unit, each NIU  
3 generally only contains a few pairs of transmitter/receivers  
4 such that multiple hops are required to relay messages from one  
5 user to another within the network. Because of this reason,  
6 network loading becomes a problem during high network  
7 utilization period. Furthermore, each NIU can only be shared by  
8 a small limited number of users due to few pairs of  
9 transmitter/receivers are available.

10 In another optional embodiment of the present invention,  
11 each fixed wavelength transmitter at the NIU is driven by a  
12 transmitter data processor. The temporal data path from the  
13 transmitter data processor is directed to the optical source  
14 while the spatial data is sent to a polarization modulator that  
15 produces symbols corresponding to various polarization states.  
16 The output of each polarization modulator at specific  
17 wavelengths circulates in the data bus. Reverse operations are  
18 carried out by a receiver. An optical signal at each wavelength  
19 is connected to a polarization demodulator. This is followed by  
20 direct photo-detection and receiver data processing. The  
21 processor demultiplexes the received TDM data and its received  
22 spatial data. With a plurality of additional TDM channels, the  
23 same data processor can now support a number of users equal to

1 the number of additional channels without installing more  
2 transmitter/receiver pairs.

3 In the present invention when increasing channel capacity  
4 and throughput of an optical communication network, a  
5 combination of polarization modulation, wavelength division  
6 multiplexing, and time division multiplexing technology is  
7 utilized. Time division multiplexing increases the number of  
8 available channels while polarization modulation increases the  
9 throughput. A systems theory related to the present invention  
10 is described by Victor Lo in "On A Statistical Space-Time  
11 Modulation Theory," Proc. IEEE P.R. Conference on  
12 Communications, Computers and Signal Processing, pp. 584-589,  
13 Victoria, B.C., Canada, June, 1989. Hardware implementation of  
14 a polarization modulator has been described by Sergio Benedetto  
15 in "Multilevel Polarization Modulation Using A Specifically  
16 Designed LiNbO<sub>3</sub>", IEEE Photonic Tech. Lett, August 1994, pp.  
17 949-951. Details of a polarization demodulator suitable for the  
18 invention are discussed in "Multilevel Polarization Shift  
19 Keying: Optimum Receiver Structure and Performance Evaluation,"  
20 IEEE Trans. on Comm., March 1994, and demodulation tracking loop  
21 in "Polarization Recovery In Optical Polarization Shift-Keying  
22 Systems" IEEE Trans. on Comm., vol. 45, no. 10, October 1997.

23 Due to the unique design disclosed in this application,

1 polarization, wavelength, and time channels enjoy total  
2 independent operation from each other. The increase in the  
3 degrees of freedom from this design adds flexibility in  
4 supporting multiple users in a large variety of optical network  
5 configurations and services. Furthermore, the independent  
6 operations imply more data channels can be added as the  
7 fiber-optic network grows under market demand. Thus, once the  
8 optical fibers are laid; only incremental costs is required to  
9 cover a fixed size network. The overall channel capacity in  
10 terms of number of channels as well as data rate throughput is  
11 simply the product of contribution from individual modulation  
12 and multiplex technology. This aggregate throughput can be  
13 orders of magnitude higher than each technology itself.

14 The above and other objects, advantages, and novel features  
15 of the invention will be more fully understood from the  
16 following detailed description and the accompanying drawings, in  
17 which:

#### 18 BRIEF DESCRIPTION OF THE DRAWINGS

19 Figure 1A is a schematic block diagram of one embodiment of  
20 a system for increasing channel capacity and throughput of  
21 optical communication networks.

22 Figure 1B is a schematic block diagram of the embodiment of  
23 one with the addition of signal amplification in the optical

1 transmission line.

2 Figure 1C is a schematic block diagram with a variation of  
3 the embodiment illustrated in Figure 1 utilizing an optical  
4 wavelength cross-connect for reusing wavelengths.

5 Figure 2A is a schematic block diagram of a variation of  
6 the invention illustrated in the first embodiment of Figure 1 in  
7 which optical sources are not directly modulated.

8 Figure 2B is a variation of the system illustrating in  
9 Figure 2A in which signal amplification is inserted in the  
10 optical transmission line.

11 Figure 2C is another variation of the system of Figure 2A  
12 including an optical wavelength cross-connect to reuse  
13 wavelengths.

14 Figure 3 is a schematic diagram illustrating a  
15 configuration of an optical wavelength cross-connect for  
16 insertion in a fiber transmission line to reuse wavelengths  
17 multiple times.

18 Figure 4A is a schematic block diagram of a transmitter  
19 data processor that essentially performs the switching function  
20 of a typical time division multiplexer.

21 Figure 4B is a schematic block diagram of a receiver data  
22 processor that demultiplexes input TDM data streams from the  
23 spatial and temporal channels into multiple output data



1 channels.

2 Figure 5A is a diagram illustrating the mapping operation  
3 of a M-level polarization modulator from digital data to  
4 polarization symbols in the Poincare sphere using Stokes  
5 parameters.

6 Figure 5B is a block diagram illustrating the  
7 implementation of the mapping operation of Figure 5A.

8 Figure 5C is a schematic block diagram illustrating a  
9 demodulator comprised of a Stokes parameters estimator, a  
10 control loop to track changes in polarization state and a  
11 decision logic block.

12 Figure 6 is a schematic block diagram according to the  
13 invention applied to a ring network having multiple add/drop  
14 nodes.

15 Figure 7 is a schematic block diagram according to the  
16 invention with the system being applied to a WDM fiber-optic  
17 star network of a plurality of wavelengths.

18 Figure 8 is a schematic block diagram illustrating one  
19 embodiment of the present invention applied to a fixed  
20 wavelength transmitter in a WDM fiber-optic data bus network  
21 operating with multiple wavelengths that is comprised of  
22 multiple Network Interface Units (NIU).

23 DETAILED DESCRIPTION OF THE INVENTION

1 In accordance with the invention disclosed herein, channel  
2 capacity of fiber-optical communication networks in a  
3 conventional Wavelength Division Multiplexing (WDM) network  
4 system can be significantly increased depending on the levels of  
5 polarization modulation. For a typical WDM system using a  
6 plurality of signal sources transmitting to a plurality of  
7 receivers at a plurality of different wavelengths, only the  
8 number of communication channels equal to the number of  
9 wavelength channels are available for data transmission. The  
10 present invention significantly increases the plurality of  
11 channels by a factor equal to the time division multiplex  
12 channels. This is achieved without requiring additional sets of  
13 laser sources.

14 One embodiment of the invention illustrated in Figure 1A  
15 shows a system with direct data modulation on optical sources.  
16 The system of Figure 1A has one set of network optical sources  
17  $12_1, 12_2$  through  $12_N$  where the 1-N represent N network optical  
18 sources. Each source  $12_1, 12_2$  through  $12_N$  is driven by a  
19 temporal path consisting of Time Division Multiplexed (TDM) data  
20 from transmitter data processors  $10_1$  through  $10_N$ . Each  
21 transmitter data processor  $10_1, 10_2, 10_N$  multiplexes a plurality  
22 of input channels of data represented by L into a time division  
23 multiplexed data stream of temporal and spatial data.

1           The output spatial data path of transmitter data processors  
2    $10_1, 10_2, 10_N$  is directed to polarization modulators  $14_1, 14_2, 14_N$   
3   while temporal data is sent to optical sources  $12_1, 12_2, 12_N$  for  
4   direct modulation. Each optical source  $12_1, 12_2, 12_N$  is  
5   connected respectively to a polarization modulator  $14_1, 14_2, 14_N$ .  
6   Polarization modulators  $14_1, 14_2, 14_N$  produce optical symbols  
7   corresponding to various polarization states. For example, with  
8   a digital modulator implementation of polarization levels  
9   represented by  $M$ , mapping to  $2^M$  distinct states, polarization  
10   modulators  $14_1, 14_2, 14_N$  generate one optical pulse at the  
11   specific state of polarization per  $M$  input pulses from the  
12   spatial path. The same optical pulse carries the temporal  
13   modulated signal originated from the optical source. The output  
14   of each polarization modulator  $14_1, 14_2, 14_N$  is sent to a  
15   Wavelength Division Multiplexer (WDM) 16 before being  
16   transmitted over transmission optical fiber 18.

17           Optical fiber 18 terminates and is connected to wavelength  
18   division demultiplexer 20. Each wavelength output of  
19   demultiplexer 20 is connected to a polarization demodulator  $22_1,$   
20    $22_2, 22_N$ . This is followed by direct photo-detection  $24_1, 24_2$   
21   through  $24_N$  and receiver data processing  $26_1, 26_2, 26_N$ . Receiver  
22   data processors  $26_1, 26_2, 26_N$  demultiplex the received TDM data  
23   from the received spatial and temporal data channels into a

1 plurality of output data channels represented by L.

2 A typical transmitter data processor 10 is illustrated in  
3 Figure 4A. Transmitter data processor 10 multiplexes input  
4 channels of data represented by L into time division multiplex  
5 data stream of temporal and spatial data by input/output (I/O)  
6 control time multiplex switch 28. The output of the transmitter  
7 data processors are then sent to the source or polarization  
8 modulator as described previously. The transmitter data  
9 processor performs the function of multiplexing multiple input  
10 channels of data into a time division multiplexed data stream of  
11 temporal and spatial data. The input and output sampling is  
12 controlled by the TDM I/O switch.

13 The mapping operation of a M-level polarization modulator  
14 from digital data to polarization symbols in a Poincare sphere  
15 using Stokes parameters is illustrated in Figure 5A while the  
16 implementation is illustrated in Figure 5B.

17 The implementation scheme of such a modulator 14 is shown  
18 in the block diagram of Figure 5B. Polarization modulator 14 is  
19 comprised of an optical input port connected to a polarization  
20 beam splitter 31 that produces two outputs with orthogonal  
21 polarization states. One such output will be rotated by  
22 polarization rotator 33 in its polarization angle while the  
23 other is phase modulated by the input data in phase modulator

35. After they transverse through directional coupler 37, the polarization angle is rotated back by polarization rotator 39 and recombined with another phase modulated signal from the input data by phase modulator 41, polarization processor 45, and polarization beamsplitter 43.

Polarization demodulator 22 is illustrated in Figure 5C. Polarization demodulator 22 is comprised of a Stokes parameter estimator 30, a control loop comprised of a track and hold circuit 32, analog to digital convertor 34, a filter 36, and digital to analog convertor 38, and decision logic block 40. The optical network system illustrated in Figure 1A operates with a plurality of wavelengths represented by  $N$  and polarization modulation levels per wavelength represented by  $M$ . In this present invention, the throughput has been increased by  $M$  times while the total number of channels has increased up to  $N \times L$  where  $L$  is the number of TDM channels. The representations by  $N$ ,  $M$ , and  $L$  are purely arbitrary and can be chosen to maximize a capacity meeting specific network requirements.

A variation of the system illustrated in Figure 1A in which like reference numbers indicate like parts throughout is illustrated in Figure 1B. In this embodiment rather than a simple transmission optical fiber 18 without signal amplification, optical amplifiers 42 are added to extend

1 transmission distance of optical fiber 18 for long-haul  
2 applications.

3 Another variation of the system and circuit illustrated in  
4 Figure 1A is shown in the schematic block diagram of Figure 1C  
5 where like reference numbers indicate like parts throughout. In  
6 this case, there are multiple sets of the circuits shown in  
7 Figure 1C to perform the multiplexing, modulation,  
8 demultiplexing and demodulation. However in this case, rather  
9 than using a single fiber-optic cable 18 as illustrated in  
10 Figure 1A having wavelength routing without reuse, an optical  
11 wavelength cross-connect is inserted in optical fiber  
12 transmission lines  $18_1$  through  $18_N$  to reuse each wavelength a  
13 number of times equivalent to N for connecting various  
14 transmitters and receivers. For example, a first user I can use  
15 one of the L channels of wavelength  $\lambda_1$  to establish a link with  
16 a user II, while simultaneously user V can reuse the same  
17 wavelength ( $\lambda_1$ ) and channel to communicate with user VI.  
18 Compared to a typical WDM fiber-optic network system operating  
19 with multiple wavelengths without reuse represented by N, the  
20 total number of channels in this unique system is increased to  
21  $(N^2 \times L)$ , where L is the number of TDM channels.

22 Another embodiment of the invention is illustrated in  
23 Figure 2A in which like reference numbers identify like parts

1 throughout. In this embodiment, optical sources  $12_1, 12_2, 12_N$   
2 are not directly modulated. In this embodiment, the optical  
3 output signal from sources  $12_1, 12_2, 12_N$  are spatial modulated in  
4 polarization and temporally modulated in amplitude, phase,  
5 and/or frequency by space-time modulators  $14_1, 14_2, 14_N$  driven by  
6 transmitter data processors  $10_1, 10_2, 10_N$ . In most applications,  
7 an indirect amplitude or indirect phase modulation is desirable  
8 to preserve the stability of optical sources  $12_1, 12_2, 12_N$ .

9 Polarization modulators  $14_1, 14_2, 14_N$  may be implemented by  
10 Electro-Optical Modulators (EOM) or Electro-Absorptive  
11 Modulators (EAM). The output of each modulator  $14_1, 14_2, 14_N$  is  
12 sent to Wavelength Division Multiplexer (WDM) 16 before being  
13 transmitted by optical fiber 18.

14 Optical fiber 18 terminates and is connected to wavelength  
15 division demultiplexer (WDM) 20. Each wavelength output of  
16 wavelength division demultiplexer is connected to a polarization  
17 demodulator  $22_1, 22_2, 22_N$ . This is followed by coherent optical  
18 demodulation in photo-detectors  $24_1, 24_2, 24_N$  and receiver data  
19 processors  $26_1, 26_2, 26_N$ . Photo-detectors  $24_1, 24_2$  through  $24_N$   
20 that provide the coherent optical demodulation can be  
21 implemented by a local optical source using homodyne or  
22 heterodyne demodulation techniques.

23 A variation of this system of Figure 2A is illustrated in

1 Figure 2B in which like reference numbers indicate like parts  
2 throughout. In this embodiment, rather than a simple  
3 transmission optical fiber 18 without signal amplification,  
4 optical amplifiers 42 are added to extend transmission distance  
5 of the fiber for long-haul applications.

6 A variation of the system of Figure 2A is illustrated in  
7 Figure 2C in which like reference numbers indicate like parts  
8 throughout. The system illustrated in Figure 2C comprises  
9 multiple sets of data processors and subsequent circuits of  
10 which can be represented by 1 through N. In this variation  
11 rather than wavelength routing without use, an optical  
12 wavelength cross-connect 44 is inserted in fiber-optic  
13 transmission lines 18<sub>1</sub> through 18<sub>N</sub> to reuse each wavelength  
14 multiple times represented by N for connecting various  
15 transmitters and receivers. Thus, cross-connect will be an NxN  
16 wavelength cross-connect.

17 For example, a first user I can use one of the L channels  
18 of wavelength  $\lambda_1$  to establish a link with a second user II,  
19 while simultaneously a fifth user V can reuse the same  
20 wavelength ( $\lambda_1$ ) and channel to communicate with a sixth user VI.  
21 Compared to a typical Wavelength Division Multiplexer (WDM)  
22 fiber-optic network system operating with multiple wavelengths  
23 of N without reuse, the total number of channels of this new



1 design is increased to  $(N^2 \times L)$ , where L is the number of TDM  
2 channels.

3 An optical wavelength cross-connect of  $N \times N$  for insertion in  
4 fiber-optic transmission lines  $18_1$  through  $18_N$  to reuse each  
5 wavelength N times for connecting various transmitters and  
6 receivers is illustrated in Figure 3. Each fiber-optic  
7 transmission line  $18_1$  through  $18_N$  feeds into wavelength  
8 demultiplexer  $46_1$  through  $46_N$ . Each demultiplexer  $46_1$  through  
9  $46_N$  provides an output to each wavelength multiplexer  $48_1$   
10 through  $48_N$  directly and by cross connection. Each multiplexer  
11  $48_1$  through  $48_N$  provides an output to fiber-optic transmission  
12 line  $18_1$  through  $18_N$  with multiple wavelength division  
13 multiplexed wavelengths represented by N per fiber.

14 The invention disclosed herein can also be applied to a  
15 conventional wavelength division multiplexing ring network as  
16 illustrated in Figure 6 wherein like reference numbers again  
17 indicate like parts throughout. Similar to the embodiment of  
18 Figure 1A, there is one set of multiple optical sources  $12_1$ ,  
19  $12_2$ , through  $12_N$  which can be represented by N. Each source  $12_1$ ,  
20  $12_2$ ,  $12_N$  is directly modulated by transmitter data processor  $10_1$ ,  
21  $10_2$ , through  $10_N$ . The output temporal data path of each  
22 transmitter data processor  $10_1$ ,  $10_2$ ,  $10_N$  is directed to each  
23 optical source  $12_1$ ,  $12_2$ ,  $12_N$ , respectively, while spatial data is

1 sent to polarization modulators  $14_1$ ,  $14_2$ , through  $14_N$ .  
2 Polarization modulators  $14_1$ ,  $14_2$ ,  $14_N$  produce optical symbols  
3 corresponding to various polarization states. The output of  
4 each polarization modulator  $14_1$ ,  $14_2$ ,  $14_N$  is sent to Wavelength  
5 Division Multiplexer (WDM)  $16_1$  before being transmitted over  
6 fiber-optics transmission line 18. The wavelength output of  
7 wavelength division multiplexer  $16_1$  is sent by fiber-optic  
8 transmission line 18 to wavelength division demultiplexer  $20_1$   
9 and add/drop node  $50_1$  to subsequent WDM  $16_2$  and multiple  
10 add/drop nodes through  $50_N$  by a series of multiplexers  $16_1$   
11 through  $16_N$  and demultiplexers  $20_1$  through  $20_N$ . Each add/drop  
12 node  $50_1$  through  $50_N$  operates in a specific wavelength with L  
13 TDM Channels.

14 The specific wavelength outputs of wavelength division  
15 demultiplexers  $20_1$ ,  $20_2$ , through  $20_N$  (WDM) are connected to  
16 polarization demodulators  $22_1$ ,  $22_2$ , through  $22_N$ . They are  
17 followed by photo-detectors  $24_1$ ,  $24_2$ , through  $24_N$  for direct  
18 photo-detection and then received by receiver data processors  
19  $26_1$ ,  $26_2$ , through  $26_N$ . Receiver data processors  $26_1$ ,  $26_2$ , through  
20  $26_N$  demultiplex the received TDM data from the received spatial  
21 and temporal data channels into multiple output data channels L.

22 The combined signals in this TDM/PM/WDM ring contains  
23 multiple wavelengths represented by N, polarization levels

represented by  $M$  and TDM channels per wavelength represented by  $L$ . Each add/drop node  $50_1$  through  $50_N$  contains a receiver transmitter pair  $52_1$  through  $52_N$  and  $54_1$  through  $54_N$  respectively. Each receiver  $52_1$  through  $52_N$  is capable of polarization demodulation, direct photo-detection and received data processing of multiple output data channels  $L$ . Transmitters  $54_1$  through  $54_N$  reverse the operation by time multiplexing multiple input data channels  $L$ , direct modulation onto optical sources followed by polarization modulation.

Wavelength division demultiplexer  $20_1$  extracts a signal at one wavelength and transmits a signal back through wavelength division multiplexer  $16_1$  at the same wavelength. The same operation is repeated on the next and subsequent add/drop nodes through  $50_N$  on optical fibers  $18_1$  through  $18_N$  until it reaches the end of the ring. The access into and egress out of the ring network is under computer control. If any receiver/transmitter unit  $52_1$ ,  $52_N$ ,  $54_1$ ,  $54_N$  wishes to transmit signals, its transmitter sends data through the TDM channel. These optical signals pass through WDM multiplexers  $16_1$  through  $16_N$  and circulate around the ring. Hence, in this embodiment, the number of network users at each add/drop nodes  $50_1$ ,  $50_N$  increases a factor of  $L$ .

A conventional WDM fiber-optics star network of multiple

1 wavelengths represented by  $N$  consists of a star coupler  
2 connected to  $N$  nodes. Each node operates with one of the  
3 optical wavelengths  $N$  and has its own laser source transmitting  
4 light at the nodes particular wavelength to the star coupler  
5 which multiplexes the optical signals at various wavelengths.  
6 One of the  $N$  nodes is used as a central office of the network.  
7 The star coupler broadcasts any optical signals from one node to  
8 all the other nodes in the network. Each node also receives and  
9 demultiplexes broadcast signals from the star coupler to  
10 determine whether it has messages sent from other nodes.

11 An adaptation of the system disclosed herein is shown in  
12 still another embodiment of the present invention illustrated in  
13 Figure 7. In this embodiment star coupler 60 is connected to  
14 multiple nodes  $62_1$  through  $62_N$ . Each star network has now  
15 increased its throughput by a multiple of  $M$  times, while the  
16 total number of channels has increased to  $N \times L$  times. Network  
17 users in the present invention at each node  $62_1$  through  $62_N$ , and  
18 70 are allocated specific TDM channels in the  
19 transmitter/receiver data processor 72.

20 The temporal data path of transmitter/receiver data  
21 processor 72 is directed to optical source 74 in each node while  
22 spatial data is sent to polarization modulator 76 in each node.  
23 Polarization modulator 76 produces optical symbols corresponding

1 to various polarization states. The output of each polarization  
2 modulator 76 in each node at the particular wavelength is sent  
3 to star coupler 60 for distribution of the wavelength  
4 multiplexed signal to all other nodes  $62_1$  through  $62_N$ . On the  
5 return path, the WDM signal is extracted from a wavelength  
6 division demultiplexer or through a wavelength tunable filter 78  
7 and polarization demodulator 80. This is followed by detection  
8 in photo-detector 82 and processed by transmitter/receiver data  
9 processor 72. Transmitter/receiver data processor 72 in each  
10 node demultiplexes received TDM data and received spatial data.

11 A conventional WDM fiber-optic data bus network operating  
12 with multiple wavelengths of  $N$  is comprised of multiple Network  
13 Interface Units (NIU) communicating over an optical fiber. Each  
14 network interface unit by which a user communicates over the  
15 network, has multiple fixed wavelength optical transmitters and  
16 multiple receivers. Due to the hardware cost of installing  
17 multiple pairs of transmitter/receivers per interface network  
18 unit, each NIU in general only contains a few pairs of  
19 transmitter/receivers, such that multiple hops are required to  
20 relay messages from one user to another within the network.  
21 Network loading then becomes a problem during a high network  
22 utilization period. Furthermore, each NIU can only be shared by  
23 a small limited number of users due to few pairs of

1 transmitter/receivers are available.

2 In yet another embodiment of the present invention  
3 illustrated in Figure 8, each fixed wavelength transmitter 84 at  
4 NIU 85 is driven by a transmitter data processor. The temporal  
5 data path from the data processor is directed to the optical  
6 source while the spatial data is sent to the polarization  
7 modulator. The modulator produces symbols corresponding to  
8 various polarization states. The output of each polarization  
9 modulator at a specific wavelength circulates in data bus 88. A  
10 reverse operation is carried out by receiver 86. This is  
11 followed by direct photo-detection and received data processing.  
12 The receiver data processor demultiplexes the received TDM data  
13 and the received spatial data with multiple additional TDM  
14 channels of L. The same data bus 88 can now support L times  
15 more users without installing more transmitter/receiver pairs.

16 Thus there has been disclosed a unique system for  
17 increasing the capacity of fiber-optical communication networks  
18 by a system of time division multiplexing, polarization  
19 modulation, and wavelength division multiplexing. The  
20 space-time modulation provides large capacity expansion by  
21 utilizing three-dimensional spatial field. This increase in  
22 channel capacity can be achieved by a combination of Time  
23 Division Multiplexing (TDM), Polarization Modulation (PM), and

1 Wavelength Division Multiplexing (WDM) technology. By  
2 maintaining independence between spatial modulation, time and  
3 wavelength division multiplexing, channels derived from  
4 wavelengths in time slots can be separately assigned. The  
5 resulting degrees of freedom increase throughput and add  
6 flexibility in supporting multiple users in a large variety of  
7 optical network configuration and services.

8 This invention is not to be limited by the embodiment shown  
9 in the drawings and described in the description which is given  
10 by way of example and not of limitation, but only in accordance  
11 with the scope of the appended claims.  
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